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THREE-DIMENSIONAL RECORDING AND REPRODUCING APPARATUS

1 BACKGROUND OF THE INVENTION

The present invention relates to an optical information recording/reproducing apparatus, and more particularly to an information recording/reproducing apparatus for achieving a high recording density.

A method for increasing the recording density for an optical information recording/reproducing apparatus has conventionally been accomplished by improving a recording plane density on a two-dimensional plane of a recording medium. However, since the size of information recording media, such as a disc, is restricted due to compactization of the apparatus, two-dimensional approach to high density will reach its limit. As a method of achieving a higher density, there has been proposed a three-dimensional recording/reproducing method which is related with the record in the depth direction of a recording medium.

For example, the JP-A-59-127237 discloses that information is recorded on two recording layers by using two lights of different wavelengths. In this event, when a light irradiates a recording layer on the incident plane side through the other recording layer, energy of the light is absorbed in the recording layer on the incident plane side, whereby information is unintentionally recorded thereon. Therefore, in JP-A-59-127237,

1 writing on the other recording layer is only allowed
after information has been recorded on the recording
layer on the incident side. More specifically, following
three-value informations can be recorded for the states
5 where information is recorded on both two recording
layers; no information is recorded on both recording
layers; and information is recorded only on the recording
layer on the incident plane side.

However, the JP-A-59-127237 does not disclose a
10 method of independently recording binary information on
each of multi-layer recording film.

Also, the JP-A-60-202545 discloses a method of
focusing a laser beam on each layer of the multi-layer
recording films. Generally, a focusing servo circuit
15 focuses a laser beam on a recording film by supplying an
electric offset when the beam is out of focus. By
utilizing this method, offset voltages corresponding to
respective inter-layer gaps in the multi-layer recording
film have previously been prepared. Then, one of the
20 offset voltages corresponding to a layer to be focused is
supplied to focus the laser beam on that layer.

However, the JP-A-60-202545 does not disclose
any means for corresponding the multi-layer recording
film to the offset voltages.

25 Also, the JP-A-60-202554 discloses a multi-
layer recording medium in which inter-layer gaps are
formed equal or larger than an operating range of a focus
error signal by more than the same operating range.

1 However, the JP-A-60-202554 does not describe specific
inter-layer gaps and an access method of actually
focusing a beam on a target layer.

SUMMARY OF THE INVENTION

5 The foregoing conventional documents disclose
performing multiple-value recording and multiplex record-
ing by using a multi-layer recording film. However, in
order to practically perform multiplex recording or
reproduction, optical systems including a focus control
10 or a track control must be investigated on the influence
of reflection or absorption of light on each layer of the
multi-layer film.

It is an object of the present invention to
provide a three-dimensional recording and reproducing
15 apparatus including an optical system capable of stably
recording and reproducing information by the use of a
recording medium comprising a multiple recording layer.

It is another object of the present invention
to provide a signal control method suitable for use in
20 the recording medium comprising a multiple recording
layer, particularly, a coding system for suppressing
cross-talk between adjacent layers, and a cross-talk
canceling system.

It is a further object of the present invention
25 to provide a structure of a recording medium suitable for
multiplex-recording, a three-dimensional data format and
a medium producing method.

1 The above objects are achieved by the following means.

 In a disc comprising a plurality of recording film layers on which optical properties are locally
5 changed by irradiating locally with a light and intermediate layers each composed of an assistant layer for the operation of the recording layer (a layer provided for the purpose of reflection protection, multiple reflection, light absorption, transfer of changes in the
10 local optical properties of the recording layer, heat insulation, heat absorption, heat generation or reinforcement) or a stack of assistant layers, each local optical property of the recording layers is individually and two-dimensionally changed by irradiating with a light
15 focused on each recording layer, thereby performing recording corresponding to modulated data "1" and "0."

 Further, in a three-dimensional recording and reproducing apparatus for detecting changes of the local optical properties as changes in a reflected light amount
20 (or a transmitting light amount) of a light spot irradiated to each assistant layer and reproducing data based on the detected change, the structure of the disc is determined as follows:

 The refractivity and thickness of the optically
25 transparent substrate are represented by N_B and d_0 , respectively. An intermediate layer and a recording layer are collected as a single layer, and first to N_{th} layers are designated sequentially from the top layer. A

1 distance between the centers of adjacent k_{th} and $(k-1)_{th}$
 recording film layers is represented by dk . The
 thicknesses of an arbitrary k_{th} recording layer and
 intermediate layer are represented by dFk and dMk ,
 5 respectively, and the real parts of the refractivities of
 the same are represented by NFk and NMk , respectively. A
 cycle of changes of the local optical properties on the
 plane of each layer is represented by b [μm]. A focusing
 optical system employs, for example, a semiconductor
 10 laser emitting a light of a wavelength λ [μm] as a light
 source. The emitted light is converted to a parallel
 light by a collimator lens and incident to the focus lens
 through a polarization beam splitter. Here, the
 numerical aperture, effective radius and focal length of
 15 the focus lens are represented by NAF , a [mm] and fF
 ($=a/NAF$), respectively. The light reflected from the
 disc passes through the focus lens and is introduced to a
 light receiving image lens by a beam splitter. A change
 of the reflected light amount is converted to an electric
 20 signal by a photo detector positioned near the focal
 point of the image lens. The numerical aperture and
 focal length of the image lens are represented by NAI and
 fI ($=a/NAI$), respectively. Assuming that the diameter of
 a light receiving plane of the optical detector is
 25 represented by D , a light focused on a k_{th} layer as a
 target layer reflected from the target layer is imaged on
 the focal point of the image lens, and a spot diameter
 Uk' on the focal plane is given by:

$$1 \quad U_k' = \lambda/NAI = \lambda \times (fI/a).$$

Next, a spot diameter $U(k+1)'$ on the focal plane from the $(k+1)_{th}$ layer spaced from the k_{th} target layer by the inter-layer distance d is given by:

$$5 \quad \begin{aligned} U(k+1)' &= a \times m^2 d / fI \\ &= NAI \cdot m^2 d \end{aligned}$$

where m is a horizontal scaling ratio of the receiving optical system.

From the above equation, assuming that the
10 diameter D of the photo detector is $D = U_k' = \lambda/NAI$, a detected amount I_n of light reflected from other layers is given by:

$$\begin{aligned} 1/10 &\geq \sum I_j (n = 1 \text{ to } N, n \neq k) / I_k \\ &= \sum [\delta^2_{jk} \times \alpha_{jk} \times (D/U_j)^2] \\ 15 \quad &= I(k-1) / I_k \\ &= \delta^2(k-1), k \times \alpha(k-1), k \times (D/U(k-1)')^2 \end{aligned}$$

where δ_{jk} represents the transmissivity of layers between the target k_{th} layer and another j_{th} layer, and α_{jk} represents a reflectivity ratio.

20 The disc structure and optical systems are designed so as to satisfy the above equation.

Further, a minimum value b_{min} of the two-dimensional cycle b is set to λ/NAF , and a maximum value b_{max} of the same is set to be smaller than $2d \times NAF$.

25 In a light receiving optical system shown in Fig. 1, optical property functions $H_0(S)$, $H_1(S)$ of a target layer plane on which recording/reproduction is performed and an adjacent layer plane spaced therefrom by

1 a distance are indicated by straight lines 13 and 14,
respectively, in Fig. 4. S represents a normalized
spatial frequency.

Now, as to the optical property function $H_1(S)$
5 for a case where out-of-focus occurs at the inter-layer
distance d, a maximum repetition b_{max} of the cycle b is
defined from $S=2$ where $H_1(S)=0$ is satisfied. By thus
defining the relationship among the cycle b of changes in
the local optical properties on the layer plane, the disc
10 structure and the light receiving optical system, inter-
layer cross-talk components are made larger than the
cycle b of changes in the local optical properties.

Further, a code which defines that a total area
occupied by local optical changes (marks) included in the
15 area defined by the spot diameter ($2d \times NAF$) on an
adjacent layer is constant is employed.

Further,

$dk = dF(k-1) + dMk + dFk \approx dMk$ (Equation 1)
and the effective refractivity NMk of the intermediate
20 layer is assumed to be equal to the refractivity NB of
the substrate.

In a disc structure where a thickness d up to
an N_{th} layer of a multi-layer disc is given by the
following equation:

25 $d \approx \sum dk + d_0$ (Equation 2)

a thickness dk of the intermediate layer of each layer
and the total number N are combined so as to satisfy a
spherical aberration amount $W40$ which is given by:

$$1 \quad W40 = 1/(8 \times NB) \times (1/NB^2 - 1) \cdot$$

$$\times NAF^4 \times \Delta d \leq \lambda/4$$

$$0.5 \times \Sigma dk = \Delta d \quad (\text{Equation 4})$$

Optical constants of the k_{th} recording layer 1,
 5 i.e., the transmissivity, reflectivity and absorption
 ratio are represented by T_k , R_k and A_k , respectively.
 Here, the relationship $T_k + R_k + A_k = 1$ is satisfied.
 The optical constants, when the local optical properties
 are changed by recording, are indicated by adding a dash
 10 "' " thereto. Generally, in thermal recording, to cause a
 change in thermal structure, an energy threshold value
 E_{th} [nJ] must exist. A light spot focused to the
 refractory limit on a target recording layer is scanning
 on the disc at a linear velocity V [m/s].

15 To locally cause a change in thermal structure
 corresponding to a modulated binary signal, a light
 intensity P (recording power) [mW] of the light incident
 to the disc should be defined. Here, given a linear
 velocity V and an irradiation time t , a light intensity
 20 density threshold value is represented by I_{th} [mW/ μm^2].

For a light intensity density I_k on a k_{th} layer
 when the focus is placed on the k_{th} layer, a $1/e^2$ spot
 area S_k when the focus is placed on the k_{th} layer is given
 by:

$$25 \quad S_k = \pi(0.5 \times \lambda/2NAF)^2$$

A light intensity P_k [mW] on the k_{th} layer is
 given by:

$$1 \quad P_k = P \cdot \delta_k$$

$$\delta_k = \Pi T_n \quad (\text{Equation 6})$$

where δ_k represents the transmissivity of layers between the light incident plane of the disc and the k_{th} recording layer, and T_n represents the transmissivity of n layers.

From Equation 6, a minimum recording power P_{min} required to enable recording on the k_{th} layer is expressed by:

$$P_{min} \geq I_{k_{th}} \times S_k / \delta_k \quad (\text{Equation 7})$$

Also, a light intensity density I_{jk} [mW] on a j_{th} layer when the focus is placed on the k_{th} layer for recording thereon is:

$$\begin{aligned} P_{jk} &= P_k \times \delta_{jk} \\ &= P \times \delta_j \end{aligned} \quad (\text{Equation 9})$$

$$15 \quad \delta_{jk} = \Pi / \Pi (= (\text{transmissivity up to } j_{th} \text{ layer} / \text{transmissivity up to } k_{th} \text{ layer}))$$

An upper limit P_{max} of the recording power for recording on a k_{th} layer without destroying data recorded on a j_{th} layer is given by the following equation:

$$20 \quad P_{max} = I_{j_{th}} \times S_{jk} / \delta_j \quad (\text{Equation 10})$$

where S_{jk} represents the diameter of a light spot on the j_{th} layer when the focus is placed on the k_{th} layer,

$$\begin{aligned} S_{jk} &= \pi [(\sum d_n) \times \text{TAN} \phi]^2 \quad (\text{when } j > k) \\ &= \pi [(\sum d_n) \times \text{TAN} \phi]^2 \quad (\text{when } j < k) \\ &= \pi [(\sum d_n) \times \text{NAF}]^2 \end{aligned} \quad (\text{Equation 11})$$

where d_n represents a thickness of an n_{th} layer.

$$\text{TAN} \phi = a / fF \approx \text{NAF}$$

1 The focusing optics, disc structure and
recording conditions are defined so as to simultaneously
satisfy Equations 6, 7, 9, 10 and 11.

 As a role of each layer, a disc is provided
5 with a ROM (Read Only Memory) layer or a WOM (Write Once
Memory) layer together with layers for recording and
reproducing user data.

 The ROM or WOM layer may be used as a manage-
ment layer, and data conditions of each layer, for
10 example, the presence or absence of data, error manage-
ment, an effective data area, the frequency of overwrite
are recorded thereon at any time.

 Also, it may be used as a spare layer such that
information is recorded thereon in place of a layer from
15 which a recording error has been detected.

 As a management format on each layer plane of
the disc, sectors and tracks are provided, and recording
is performed sequentially from the top layer, i.e., 1_{st} -
k_{th} - N_{th} layers or from the lowermost layer, i.e., N_{th} -
20 k_{th} - 1_{st} layers. Note, however, that recording proceeds
to the next layer after all user sectors and tracks have
been filled with information in each layer.

 While recording proceeds to the next layer
after all user sectors and tracks have been filled with
25 information in each layer, the order of layers to be
accessed for recording is at random.

 While layers to be recorded are randomly
accessed, after data has been recorded in a sector of a

1 layer, the same sector of the next layer is filled. When
the same sector of all layers has been filled, data is
recorded on the next sector.

On a track, random access is performed in the
5 layer direction. In this case, a variable length block
is employed, not a fixed block management based on the
sector.

As a light spot positioning mechanism, a two-
dimensional actuator for driving a focus lens in the
10 layer direction and the radial direction of the disc or a
combination of a one-dimensional actuator for driving a
focus lens only in the layer direction and a galvano
mirror for deflecting light flux in the radial direction
of the disc is employed, where a layer address recorded
15 on a preformat portion is read by a layer number
detecting circuit to recognize the number of a layer on
which the focus is currently being placed. Then, it is
recognized in which of upward or downward direction (+ or
- (k-j)) and how many layers ($|k-j|$) the spot should jump
20 from the j_{th} layer on which the spot is now focused to the
 k_{th} target layer instructed by an upper level controller,
and a layer jump signal generating circuit is instructed
to generate a jump force signal which is inputted to an
AF actuator driver.

25 The jump signal is composed of a pair of
positive-polarity and negative-polarity pulses for a one-
layer jump, and replaces the positive or negative pulse
in accordance with the upward or downward jumping

1 direction. The first pulse is used to drive the spot
approximately by a jumping distance in a jumping
direction, and the next polarity inverted pulse is
provided to stabilize the spot so as not to excessively
5 jump. A number of pairs of pulses equal to the number of
layers over which the spot jumps is inputted to a driver
circuit. Next, the layer number is detected, and $j=k$ is
recognized.

A zero-cross pulse of the AF error signal and a
10 total light amount pulse are used as gates, and a cross
layer signal detecting circuit is provided for detecting
the detection of a focused point on each recording layer.

A saw-tooth wave is generated from an AF
actuator shift signal generating circuit so as to shift a
15 focus position at least from the top layer to the lower-
most layer of the disc, and the AF actuator is driven by
this saw-tooth wave, wherein the focal points on T layers
are counted by the cross layer signal detecting circuit,
and the top layer ($n=1$) is recognized from an upper limit
20 of an up pulse when the lens is shifted upwardly while
the lowermost layer ($n=N$) is recognized from a lower
limit of a down pulse when the lens is shifted down-
wardly, thereby always recognizing the focus position in
the layer direction of the disc.

25 When recording is to be stably performed on a
target k_{th} recording layer, a recording power P (light
intensity) is set in consideration of the transmissivity
up to the k_{th} layer ($\sum T_n$ ($n=1, 2, \dots, k-1$)). Also, the

1 transmissivity up to the k_{th} layer is set for recognition
of the layer address.

The recording power is set by address recognition in consideration of a ratio of the transmissivity up
5 to the k_{th} layer ($\sum T_n$ ($n=1, 2, \dots, k-1$)) upon shipment of
the disc (or designed value) to the transmissivity up to
the k_{th} layer ($\sum T_n'$ ($n=1, 2, \dots, k-1$)) immediate before
recording, i.e., a change G in transmissivity.

A management layer for layer data is provided
10 for recording on which layer recording is being
performed. The management layer is reproduced before
recording on a target layer to recognize the trans-
missivity up to the k_{th} layer ($\sum T_n'$ ($n=1, 2, \dots, k-1$))
immediate before recording and a change G in trans-
15 missivity.

The change G in transmissivity may be obtained
by previously reproducing an area to be recorded before
recording on the target layer.

As a method of previously reproducing an area
20 to be recorded, a reproduction check is done in the first
rotation of the disc in a recording mode, recording is
performed in the next rotation, and then a recording
error check is done in the third rotation. In this
event, a plurality of spots are employed, and the
25 reproduction check is done by a preceding spot.

The reproduction check employs a reproduced
signal $C'k(t-\tau)$ reproduced by the preceding spot, where τ
represents the distance between the preceding spot and a

1 recording spot converted into a time. Here, the
transmissivity change G may be calculated as a square
root of a ratio of a reproduced signal Ck' in a state
where the spot is focused on the target k_{th} recording
5 layer to a reproduced signal Ck as a design value which
has previously been set upon shipment of the disc.

In the reproduction check, the value of the
reproduced signal Ck may be recorded on a non-recording
area previously provided as a check area in a disc format
10 with respect to the layer direction on a disc plane.

As a reproduction control circuit, reflected
light components from adjacent layers which particularly
include a majority of inter-layer cross-talk is detected,
in addition to the detection of reflected light
15 components from a target layer, and mutually included
components are removed by a calculation.

Three photo detectors are positioned on imaging
planes of a target k_{th} layer and the adjacent $(k+1)_{th}$ and
 $(k-1)_{th}$ layers on the light receiving plane side when the
20 focus is placed on the k_{th} layer. The shape of the photo
detectors are selected to be a circle, the diameter D of
which is given by $D = (\lambda/NAI)$. Alternatively, pinholes
are used to restrict light receiving areas. Then, the
following calculation is performed for a reproduced
25 signal by the photo detector on the k_{th} layer, a
reproduced signal $C(k-1)$ by the photo detector on the
 $(k-1)_{th}$ layer, and a reproduced signal by the photo
detector on the $(k+1)_{th}$ layer.

$$\begin{aligned}
1 \quad \text{Calculation } F &\equiv Ck - \gamma \times C(k - 1) - \gamma \times C(k + 1) \\
&\equiv CkR + \beta \times C(k - 1)R + \beta \times C(k + 1)R \\
&\quad - \gamma \times \{C(k - 1)R + \beta \times CkR + \beta \times C(k - 2)R\} \\
&\quad - \gamma \times \{C(k + 1)R + \beta \times CkR + \beta \times C(k + 2)R\}
\end{aligned}$$

5 where β represents a ratio of cross-talk components included in each signal to necessary signal components.

Since $C(k - 2)R$ and $C(k + 2)R$ are sufficiently small and frequency components are also low, these terms can be neglected.

$$\begin{aligned}
10 \quad \text{Thus, } F &\equiv (1 - 2\gamma\beta) \times CkR + (\beta - \gamma) \times C(k - 1)R \\
&\quad + (\beta - \gamma) \times C(k + 1)R
\end{aligned}$$

Here, if $\gamma \equiv \beta < 1$,

$$F \equiv (1 - \beta)^2 \times CkR$$

By employing the calculation function given by
15 the above equations, signal components on the target layer alone can be derived.

A plurality of spots are employed. A spot having the same spot diameter as an out-of-focus spot on the adjacent layers when the focus is placed on the k_{th}
20 layer are used to scan the two adjacent layers prior to the spot focused on the k_{th} layer, to obtain reproduced signals from these layers, and the above calculation is performed.

As shown in Fig. 18, a diaphragm is inserted to
25 reduce the effective aperture of the focus lens. Specifically, the effective diameter a' is reduced to $[\lambda / (2d \times NAF^2) \times a]$.

The optical axis is considered for three

1 separate optical systems employing three different spots,
and the numerical aperture of the focus lenses are
reduced in two optical systems with preceding spots.

Specifically, $NAF' = \lambda/2d \times NAF$ is given.

5 A reproduced signal detected by the preceding
spot is multiplied with a weighting function 80 derived
by approximating a Gaussian distribution, which is an
intensity distribution of the spot, to a triangle
distribution, and integration is performed to this
10 product.

In a weight setting circuit for setting each
calculation coefficient γ ($\equiv \beta$), mark recording areas on
at least three layers including upper and lower adjacent
layers are located as a disc format such that they are
15 not included in the same light flux, and $h(k-1)/h_k$ and
 $h(k+1)/h$ are set to $\beta(-1)$ and $\beta(+1)$.

By employing a plurality of spots and placing
the focus on each layer, recording/reproduction is
performed simultaneously on two or more layers, i.e.,
20 parallel recording/reproduction is achieved.

A recording medium, the transmissivity of which
is increased after recording, is employed.

Guide grooves in each layer plane of the multi-
layer disc and prepits such as address are provided in a
25 UV cured resin layer for each layer and formed by using a
transparent frame for each layer by a 2P method which
employs the light incident from the plane of the frame.

The intermediate layer is provided with a

1 quarter wave plate layer.

By applying the above structure, there can be provided a three-dimensional recording/reproducing apparatus including an optical system which enables
5 stable information recording and reproduction.

Particularly, since a photo detector in a predetermined shape is disposed on the focal plane of the optical system, when information recorded on a target recording layer is to be reproduced from among a
10 plurality of recording layers constituting a recording medium, leak of reflected lights from other recording layers are reduced and signal components on the target recording layer alone can be detected.

A predetermined relationship is established
15 between a recording frequency of information on a recording layer subjected to reproduction and the numerical aperture of a focus lens in the optical system, whereby cross-talk components from adjacent layers included when information is being reproduced from the
20 target layer is limited to direct current components (of a fixed value), and signal components from the target layer alone can be extracted by removing the direct current components.

Further, spherical aberration caused by a
25 change in optical distance from one layer to another is suppressed within a tolerable value, and a light spot at the diffraction limit can be formed on each recording layer.

1 Also, a recording power can be set to an
incident light which allows stable recording on a target
layer without destroying data on other recording layers
during the recording process.

5 BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1, comprising Figs. 1A - 1C, shows the
principle of a recording/reproducing system according to
the present invention;

Fig. 2, comprising Figs. 2A and 2B, shows the
10 structure of basic optical system which is applied to the
present invention;

Fig. 3 shows the principle of a recording
system according to the present invention, where Fig. 3A
is a graph showing a light intensity on each layer; Fig.
15 3B is a graph showing spot plane densities on other
layers when the focus is placed on a k-layer; and Fig. 3C
is a graph showing power densities on other layers when
the focus is placed on the k-layer;

Fig. 4, comprising Figs. 4A - 4C, shows the
20 principle of a reproducing system according to the
present invention;

Fig. 5, comprising Figs. 5A - 5C, is a diagram
showing a disc format according to the present invention;

Fig. 6 is a block diagram showing the whole
25 arrangement of a three-dimensional recording/reproducing
apparatus according to the present invention;

Figs. 7A, 7B are block diagrams showing a

1 recording control method according to the present invention;

Fig. 8 shows RBW (Read Before Write) by a preceding beam;

5 Fig. 9 shows a concept of a recording control method according to the present invention;

Fig. 10 shows an example of a three-layer film structure and its recording characteristic, where Fig. 10A is a diagram illustrating a three-layer film structure of a recording medium, and Fig. 10B is a graph illustrating the recording characteristic;

Fig. 11 is a cross-sectional view showing the structure of a phase change type information recording medium used in an embodiment of the present invention;

15 Figs. 12A, 12B are partial cross-sectional view of a third information recording medium used in the present invention;

Fig. 13 is a block diagram showing a reproduction control method according to the present invention;

20 Figs. 14 - 16 show a concept of the reproduction control method of the present invention;

Fig. 17 shows an optical system for realizing the reproduction control method of the present invention, where Fig. 17A illustrates the principle of the optical system; Fig. 17B an actual optical system; and Fig. 17C the formation of a pinhole;

25 Fig. 18 is a diagram showing the structure of an optical system for realizing the reproduction control

1 method of the present invention;

Fig. 19 shows a calculation coefficient γ ($\equiv \beta$)
check area and a diagram of the principle;

Fig. 20 shows a disc structure for realizing a
5 third reproducing method according to the present inven-
tion;

Fig. 21 shows a disc structure to which a two-
dimensional recording/reproducing method is applied;

Fig. 22 shows another disc structure to which a
10 two-dimensional recording/reproducing method is applied;

Fig. 23 is a block diagram for explaining a
layer access in the present invention;

Fig. 24, comprising Figs. 24A - 24C, shows a
concept of how out-of-focus is detected in each recording
15 layer;

Fig. 25 is a block diagram for explaining a
layer access in the present invention;

Fig. 26 shows detection of out-of-focus in a
recorded layer, where Fig. 26A is a graph illustrating a
20 signal indicative of an out focus on a recorded layer;
and Fig. 26B is a block diagram illustrating an out-of-
focus detecting circuit; and

Fig. 27 is a diagram for explaining a method of
reducing interference of reflected lights between adja-
25 cent layers according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the present invention will

- 1 hereinafter be described in the following order:
- (1) Principle of Three-dimensional Recording/reproducing Method;
 - (2) Three-dimensional Disc Format and Data Management;
 - 5 (3) Structure of Apparatus;
 - (4) Access Method;
 - (5) Recording Control Method;
 - (6) Reproduction Control Method; and
 - (7) Embodiment of Disc Structure and Disc Producing
 - 10 Method.

- (1) Principle of Three-dimensional recording/reproducing method

The principle of recording and reproduction performed by a three-dimensional recording/reproducing apparatus according to the present invention will first be explained with reference to Fig. 1. Information is recorded on and reproduced from a disc 4 in which a combination of a recording layer 1 and an intermediate layer film 2 is stacked on an optically transparent

20 substrate 3 a plurality of times. The recording layer 1 is such that its optical properties change by a local light irradiation. The intermediate layer 2, serving as an assistant for the recording layer 1, consists of a layer or a stack of layers provided for the purpose of

25 reflection protection, multiplex reflection, light absorption, transfer of local optical property changes on the recording layer, heat insulation, heat generation,

reinforcement and so on. A light spot focused on each layer is irradiated thereonto to two-dimensionally change the local optical properties of recording layers independently of each other. Then, recording is performed on each layer corresponding to modulated data "1" and "0," and the light spot is irradiated onto a recording layer whose optical properties have been changed to detect a change in a reflected light amount (or a transmitting light amount) to reproduce data.

In the disc 4 shown in Fig. 1B, the refractivity and the width of the optically transparent substrate 3 are designated NB and d_0 , respectively. Further, the intermediate layer and the recording layer 1 are blocked as a combination of layers k , and these combinations are sequentially numbered from 1 to N from the top layer (on the light incident plane side). The distance between adjacent layers is in principle indicated by d_k which is the distance between the centers of adjacent k_{th} and $(k+1)_{th}$ recording film layers in the thickness direction. Further, a film thickness of an arbitrary k_{th} recording layer is designated dFk ; the real part of the refractivity of the same NFk ; the film thickness of the intermediate layer 2 dMk ; and the real part of the refractivity of the same NMk . Also, a cycle of changes in the local optical properties on the plane of each layer is designated b [μm]. A focusing optical system shown in Fig. 1A employs as a light source, for example, a semiconductor laser 5 which emits the light

1 with wavelength λ [μm]. The light emitted from the
semiconductor laser 5 is converted to a parallel light by
a collimator lens 6, and is incident to a focus lens 8
through a polarization beam splitter 7. Here, the
5 numerical aperture, effective radius and focal length are
designated NAF, a [mm] and f_F ($= a/\text{NAF}$), respectively. A
light spot 11 at diffraction limit is focused on each
recording layer to be irradiated thereon.

As light receiving optical system, an example
10 of reflection light receiving system is shown. The light
reflected from the disc 4 is led through the lens 8 to an
image lens 9 for receiving light by the beam splitter 7.
A photo detector 10 is disposed in the vicinity of the
focal point of the lens 9 such that a change in a
15 reflected light amount detected by the detector 10 is
converted to an electric signal. The photo detector 10
is illustrated in Fig. 1C. The numerical aperture and
focal length of the image lens 9 are designated NAI and
 f_I ($= a/\text{NAI}$), respectively. Also, the diameter of a
20 light receiving plane of the photo detector 10 is
designated D ($= \text{NAI}/\lambda$).

Although in this embodiment, infinite optics of
Fig. 2A is shown as an example of the optical system,
limited optics shown in Fig. 2B may also be used to
25 produce similar effects. Also, as the light receiving
optical system, transmitting light detecting scheme can
be used to produce similar effects to this embodiment.

In the three-dimensional recording/

1 reproduction, it is necessary for performing recording/
reproduction to focus a light spot at the diffraction
limit on each layer. With a conventional optical disc, a
light spot is focused on a recording plane through a
5 substrate for protecting a recording film. In this
event, the focus lens 8 should be designed so as to
prevent spherical aberration from occurring to distort
the light spot, in consideration of the refractivity of
the substrate and the thickness of the recording film.
10 However, in the multi-layer disc 4, the
influence of layer films other than a layer to be
recorded cannot be neglected. For example, as indicated
in a known literature by Kubota et al, entitled "Optical
Code 14, Analysis of Jitter of Eye Patterns on an Optical
15 Disc I - V", 1985, as the number of layers other than a
layer subjected to recording increases, spherical
aberration also increases, which hinders the light from
being focused to the diffraction limit. To solve this
problem, the present invention proposes a design of a
20 focus lens for providing a light spot having a sufficient
range for recording and reproduction, and a disc struc-
ture. It is assumed for simplicity of a designing method
that the film thickness d_{fk} of the recording layer 1 is
thin enough relative to the film thickness d_{mk} of the
25 intermediate layer 2 to be neglected. Namely, the
following equation 1 is satisfied:

$$d_k \approx d_{mk} \quad (\text{Equation 1})$$

Further, an intermediate layer k is assumed to

1 have the same refractivity NB as the substrate 3. In
this case, a thickness d of the disk from the light
incident plane to the N_{ch} layer is:

$$d = \sum dk + d_0 \quad (\text{Equation 2})$$

5 On the other hand, at Rayleigh limit, a
spherical aberration amount W40 = $\lambda/4$ is given as a
tolerable value where 80% of a focus spot without
aberration is ensured as a peak intensity.

The spherical aberration amount W40 caused by a
10 change in film thickness Δd from the first to N_{ch} layers
is given by the following Equation 3:

$$W40 = 1/(8 \times NB) \times (1/NB^2 - 1) \times NAF^4 \times \Delta d$$

(Equation 3)

Thus, the design of a focus lens and the disc
15 structure are determined so as to satisfy $W40 \leq \lambda/4$. As
an example, when a glass substrate with the refractivity
NB equal to 1.5 is used as the substrate 3, a UV cured
resin having a refractivity substantially equal to that
of glass is used as the intermediate layer, and the focal
20 length NAF of the focus lens 8 is selected to be 0.55, Δd
 $\leq 50\mu\text{m}$ is derived from Equation 3. Here, by combining
the thickness dk of the intermediate layer of each layer
and the total number N so as to satisfy the following
Equation 4:

25 $d_0 = 1.2 \text{ mm} - \Delta d = (1.15 \text{ to } 1.2 \text{ mm})$
 $0.5 \times \sum dk = \Delta d \quad (\leq 50 \mu\text{m})$

(Equation 4)

a focus lens for a substrate thickness equal to 1.2 mm

1 used for a conventional optical disc can be used as it is
to form an optical spot sufficiently usable for recording
on and reproducing from each of the first to Nth layers.
As a combination, with the thickness of the intermediate
5 layer $dM_k = 10 \mu\text{m}$ and the thickness of the recording
layer $dF_k = 200\text{\AA}$, $d_0 = 1.15 \text{ mm}$, $\sum d_k = 100.4 \mu\text{m} \approx 100 \mu\text{m}$,
and the total number $N = 10$ are possible.

With Equation 4, spherical aberration is zero
on the fifth layer, while maximum spherical aberration
10 within the tolerable value occurs on the topmost and
lowermost layers. Such spherical aberration can also be
corrected. The wave optics indicates that spherical
aberration can be corrected by shifting the focus
position. This may be done on condition of $W_{40} = -W_{20}$
15 $= -0.5 \times NAF^2 \Delta z$, and $\Delta z = -2/NAF^2 \times W_{40}$, where W_{20}
represents aberration due to out-of-focus, and Δz the
out-of-focus amount. In the above example, spherical
aberration W_{k40} occurring on the k_{th} layer spaced from the
fifth layer by an inter-layer distance $\Delta d_k = (k-5) \times d$ is
20 derived from Equation 3, and an out-of-focus amount Δz_k
for correcting this aberration is $\Delta z_k = -2/NAF^2 \times W_{k40}$.

On the lowermost layer ($k=10$), an out-of-focus
amount equal to $1.4 \mu\text{m}$ may be given as an offset, and on
the topmost layer ($k=1$), $-1.4 \mu\text{m}$ may be given likewise.

25 A second problem for performing recording/
reproduction lies in a thermal recording process.
Restrictive conditions for the recording are the
following two items:

- 1 <1> A sufficient and stable recording power density can
be given to a target recording layer; and
2 <2> When recording is performed on an arbitrary k_{th}
layer, data recorded on other layers are not destroyed.

5 Factors related to these conditions are
classified into those concerning the light intensity and
those concerning the thermal conductivity. Here, the
former factors will be described. The latter factors can
be attended to by providing the intermediate layer 2 with
10 a heat insulating effect. This method will be shown
later in the paragraph describing "Embodiment of
Recording Medium".

To satisfy these two items, the present inven-
tion primarily optimizes the disc structure and the
15 focusing optical system.

Referring to Fig. 1, it is assumed for
simplicity of the explanation, the substrate 2 and the
intermediate layer 3 both have the transmissivity equal
to 100%, by way of example. Also, optical constants of
20 the k_{th} recording layer, i.e., the transmissivity,
reflectivity and absorption ratio are represented by T_k ,
 R_k and A_k , respectively. Here, the relationship $T_k + R_k$
 $+ A_k = 1$ is satisfied. The optical constants, when the
local optical properties are changed by recording, are
25 indicated by adding a dash "'" thereto. Generally in the
thermal recording, the thermal structure on a recording
film changes due to a temperature rise caused by a heat
generated by the optical film absorbing the light and

1 thermal diffusion occurring with thus generated heat as a
 heat source. This change in thermal structure corre-
 sponds to a movement of a recording film due to melting
 in a hole forming type recording medium; crystallization
 5 and non-crystallization in a phase change type recording
 medium; and inversion of vertical magnetization in a
 magneto-optical recording medium. This change in thermal
 structure may cause a change in the local optical
 properties. To cause the change in thermal structure, an
 10 energy threshold value E_{th} [nJ] must exist irrespective
 of the kind of recording film. In a recording process,
 an optical spot 11 focused on a target recording layer at
 the diffraction limit is scanning on a disc at a linear
 velocity V [m/s]. To locally give rise to a change in
 15 thermal structure corresponding to modulated binary
 signals, the intensity P (recording power) [mW] of the
 light irradiated on the disc plane is modulated by a time
 t [s]. If the linear velocity V and the irradiation time
 t are given, the energy threshold value E_{th} can be
 20 discussed with a light intensity density threshold value
 I_{th} [mW/ μm^2].

To satisfy the foregoing item <1>, the follow-
 ing Equation 5 may stand with respect to the light
 intensity density I_k on the k_{th} layer when the light spot
 25 is focused on the k_{th} spot:

$$I_k = P_k/S_k \geq I_{k_{th}} \quad (\text{Equation 5})$$

where I_{kth} : Light intensity density threshold value on
 the k_{th} recording layer (mW/ μm^2);

1 Sk: $1/e^2$ spot area when the light spot is focused on
the k_{th} layer: $Sk = \pi(0.5 \times \lambda/2NAF)^2$

Further, the diameter of the light spot focused
at the diffraction limit is represented by λ/NAF .

5 A light intensity P_k [mW] on the k_{th} layer is:

$$P_k = P \cdot \delta k, \quad \delta k = \Pi T_n \quad (\text{Equation 6})$$

where δk represents the transmissivity of an area between
the light incident plane and the k_{th} recording layer of
the disc, and T_n the overall transmissivity of n layers.

10 The transmissivity T_n is as shown in Fig. 3a. From
Equations 5 and 6, a minimum recording power P_{min}
required to record on the k_{th} layer is given by Equation
7:

$$P_{min} \geq I_{k_{th}} \times Sk / \delta k \quad (\text{Equation 7})$$

15 Generally, the lowermost layer N exhibits the
lowest light intensity. If a medium is such that the
transmissivity T_n decreases after recording has been
performed on n layers ($n = 1$ to $N-1$), the transmissivity
 T_n is replaced by T_n' (transmissivity after recording).

20 To satisfy the foregoing item (2), the light
intensity density L_{jk} [mW/ μm^2] on the j_{th} layer when the
focus is placed on the k_{th} layer for recording on the k_{th}
layer may satisfy Equation 8:

$$I_{jk} = P_{jk} / S_{jk} < I_{j_{th}} \quad (\text{Equation 8})$$

25 $P_{jk} = P_k \times \delta j_k = P \times \delta j \quad (\text{Equation 9})$

where $\delta j_k = \Pi t_n / \Pi t_n' (= (\text{transmissivity of layers up to
the } j_{th} \text{ layer}) / (\text{transmissivity of layers up to the } k_{th} \text{ layer}))$.

1 $T1 = T2 = T3 = 0.8$; and $A1 = A2 = A3 = 0.1$. Also, a
 linear velocity V is set to 7 m/s, an irradiation time t
 to 100ns to 500ns, and light intensity density threshold
 values of the recording layers at this time are set to
 5 $I_{1th} = I_{2th} = I_{3th} = 2.53 \text{ (mW/}\mu\text{m}^2\text{)}$. With these prior
 conditions, a recordable inter-layer distances $d = d1 =$
 $d2 = d3$ and a recording power range are determined.

Fig. 10B shows a power of the light irradiated
 onto a disc and a modulation degree of a reproduced
 10 signal generated corresponding to the light power when
 the focus is placed on each recording layer of a disc
 where recording has not been performed other than on a
 target recording layer. The signal modulation degree
 indicates a standard on the size of a mark formed by a
 15 change in local optical properties on the surface of each
 recording layer. When the mark is large enough such as
 the diameter of the focus spot, the modulation degree
 presents a tendency of saturation. The ordinate in Fig.
 10B indicates the normalized modulation degree with a
 20 saturation value being determined to be one. In Fig.
 10B, a threshold value power which can form the mark is
 $4\text{mW} (= I_{th} \times S1)$ on the first layer, and $5\text{mW} (= I_{th} \times$
 $S2/S1)$ on the second layer. The power on the third layer
 ($k=3$) determines a minimum power which is calculated from
 25 Equations 5, 6 and 7:

$$\delta_3 = \Pi T_n = 0.64$$

$$S_3 = \pi(0.5 \times \lambda / \text{NAF})^2 = 1.58 \text{ (}\mu\text{m}^2\text{)}$$

$$P_{min} \geq I_{3th} \times S_3 / \delta_3 = 6.3 \text{ mW} \quad (\text{Equation 12})$$

1 From (Equations 8, 9 and 11:

$$S_{23} = 0.95 \times d^2$$

$$S_{13} = 3.8 \times d^2$$

$$S_{23} = 1.25, S_{13} = 1.5625$$

5 $P_{23} = 1.25 \times P_3 = 0.8 \times P$

$$P_{13} = 1.5625 \times P_3 = P$$

$$I_{23} = 0.8 \times P / (0.95 \times d^2) = 0.886 \times P / d^2$$

$$I_{12} = P / (3.8 \times d^2) = 0.07 \times P / d^2$$

$$I_{23} < I_{2th} = 2.53$$

10 $d > 0.59 \times \sqrt{P_{min}} = 1.48 \mu m$

(Equation 13)

For example, when $d = 2.5 \mu m$, P_{max} is calculated to be 16 mW ($P_{3max} = 10$ mW), whereby a signal can record a sufficient mark as shown in Fig. 10B.

15 By thus designing the focusing optical system, data can be highly reliably recorded on a target layer without destroying recorded data on other layers.

A third problem for recording/reproduction lies in a reproduction process. Restrictive conditions for reproduction are the following items:

20

<3> Noise components are reduced to be minimum. Here, inter-layer cross-talk noise should be reduced.

<4> Signal components from a target layer is made maximum.

25 A first method for achieving the item <3> will be shown.

A first method consists of optimizing the light receiving optical system in Fig. 1. In other words, an

1 amount of the light reflected from layers other than the
 target layer is made sufficiently small. Consequently,
 inter-layer cross-talk can be reduced, with the result
 that reproduction can be performed with a large S/N
 5 ratio. In Fig. 1A, a reflected light amount from a
 recording layer from which data is to be reproduced is
 all detected by the photo detector 10 disposed on the
 focal point of the image lens 9. This operation is now
 explained with reference to Fig. 1C. Unlike a reflected
 10 light from a recording layer from which data is to be
 reproduced, a reflected light from an adjacent layer
 spreads over a focal plane 12 of the image lens, as
 indicated by a broken line. Therefore, by restricting
 the size of the photo detector 10, such a reflected light
 15 from an adjacent layer can be reduced. Hereinafter,
 restriction of the size of the focal plane will be shown.

When the light spot 11 is focused on the k_{th}
 recording layer as a target layer, the diameter of the
 light spot 11 which provides an intensity equal to a peak
 20 value multiplied by $1/e^2$, i.e., a spot diameter U_k is
 given by $U_k = (\lambda / NA_F)$. A reflected light from the
 target layer is imaged at the focal point of the image
 lens 9. A spot diameter U_k' on this focal plane 12 is
 given by:

$$\begin{aligned}
 25 \quad U_k' &= mU_k = m \times (\lambda / NA_{FL}) = (NA_F / NA_I) \times (\lambda / NA_F) \\
 &= \lambda / NA_I = \lambda \times (f_I / a)
 \end{aligned}$$

(Equation 14)

where m : a horizontal scaling ratio of the light

1 receiving optical system. Next, a spot diameter $U(k\pm 1)$
 on the focal plane from the $(k\pm 1)_{th}$ layer spaced from the
 k_{th} target layer by the inter-layer distance d is
 calculated. A distance d' between a position at which a
 5 reflected light from the $(k\pm 1)_{th}$ layer is focused by the
 image lens 9 and the focal plane is given by:

$$d' = Y \times d = m^2 \times d \quad (\text{Equation 15})$$

where Y : a vertical scaling ratio.

$$\begin{aligned} U(k\pm 1)' &= d' \times \tan \phi I = d' \times a / (fI + d') \\ 10 \quad &= m^2 d \times a / (fI + m^2 d) \end{aligned}$$

Here, if $fI > m^2 d$ stands,

$$U(k\pm 1)' \approx a \times m^2 d / fI = NAI \cdot m^2 d \quad (\text{Equation 16})$$

Assuming that the diameter D of the photo
 15 detector is given by $D = Uk' = \lambda / NAI$ from the above
 equations, an area ratio ϵ is calculated by $\epsilon =$
 $(D/U(k\pm 1)')^2$. Thus, the reflected light amount from the
 adjacent layer can be reduced, a change in reflected
 light amount from the target layer can be detected with a
 20 high S/N ratio as compared with a case where the diameter
 of the photo detector is not restricted.

Actually, a reflected light amount from another
 recording layer is detected in consideration of the
 transmissivity δ_{jk} between the target k_{th} layer and the
 25 other j_{th} layer as well as a reflectivity ratio α_{jk} .
 Assuming that an inter-layer cross-talk noise amount
 required for a reliable signal detection is -20db (1/10),
 the following equation may generally be satisfied:

1 If a reflected light amount from n layers
 detected by the photo detector 10 is represented by I_n ,

$$1/10 \geq \sum I_j (n = 1 \text{ to } N, n \neq k) / I_k$$

$$= \sum [\delta^2 j k \times \alpha j k \times (D/U j')^2]$$

5 (Equation 17)

Note, however, that hereinafter the layer
 $(k-1)_{th}$ adjacent to the k_{th} layer will alone be considered.
 Although the influence exerted by other layers may be
 likewise considered, the value is ignorably small.

10 (Equation 17) $\approx I(k-1)/I_k = \delta^2(k-1),$
 $k \times \alpha(k-1), k \times (D/U(k-1)')^2$

(Equation 17.5)

For example, with $\lambda = 0.78 \mu m$, $NAF = 0.55$ and
 $fI = 30mm$, in a case where $NAI = 0.075$, $m = 7.33$ and $m^2 =$
 15 53.8 , $D = Uk' \approx 10.4 \mu m$.

Given Fig. 10 as an example, from $\delta^2_{23} = 1.25$
 and $\alpha_{23} = 1$, a suppression ratio is expressed by $\epsilon \times \delta^2_{23}$
 $\times \alpha_{23}$.

$$I_2/I_3 = \delta^2_{23} \times \alpha_{23} \times \epsilon = \delta^2_{23} \times \alpha_{23} \times (D/U_2')^2$$

$$= \delta^2_{23} \times \alpha_{23} \times (\lambda/NAI)^2 / (NAI \times m^2 d)^2 \delta^2_{23}$$

$$\times \alpha_{23} \times (\lambda/NAF^2/d)^2$$

(Equation 18)

If d is calculated so as to satisfy $(I_2/I_3) \leq$
 1/10:

25
$$d \geq \sqrt{(10 \times \alpha_{23})} \times \delta_{23} \times (\lambda/NAI^2/m^2)$$

$$= \sqrt{(10 \times \alpha_{23})} \times \delta_{23} \times (\lambda/NAF^2) \approx 12.9 \mu m$$

(Equation 19)

While the influence of cross-talk from the

1 second layer has been considered in this example, the
influence of cross-talk from the first layer can also be
calculated, however, its value (I_1/I_3) = 0.024 (=-32dB)
is small enough to be neglected.

5 In the foregoing example, the diameter D of the
photo detector is determined to be $D = Uk' = \lambda/NAI$,
however, there is a certain degree of freedom in design,
including a position shift of the photo detector, such
that inter-layer cross-talk may present a certain value.

10 Next, a second method will be shown to achieve
the item <3>.

The second method defines the relationship
between a cycle b of changes (mark) in the local optical
properties on a recording layer plane, the disc structure
15 and light receiving optical system, thereby making inter-
layer cross-talk components larger than the cycle b of
changes in the local optical properties. Stated another
way, frequency components of the inter-layer cross-talk
are made smaller than a signal band of data, thereby
20 reproducing data on the plane of a target layer with a
high S/N ratio. The principle of this method will be
explained with reference to Figs. 1 and 4. Although the
diameter of an optical detector is not restricted in
order to distinguish the second method from the first
25 method, the second method may be combined with the first
method to provide a higher S/N ratio.

Next, the item <4> will be examined.

Since a light spot at the diffraction limit is

1 formed on a target layer, if a two-dimensional cycle b is
as long as a spot diameter (λ/NAF) on the target layer,
the light spot can provide a sufficient resolution. In
other words, if a minimum value b_{min} of the two-
5 dimensional cycle b is set to (λ/NAF), signal components
can be extracted with a sufficiently large proportion.
This is a condition for satisfying the item <4>. A spot
diameter on an adjacent layer, since the light spot is
out of focus on this layer, is expressed by ($2d \times NAF$),
10 where d represents an inter-layer distance, and accord-
ingly the optical resolution is degraded. Therefore, by
utilizing this characteristic, if a maximum value b_{max} of
the two-dimensional cycle b is set to be smaller than ($2d$
 $\times NAF$), leak of signal components from the adjacent
15 layer, i.e., frequency components of the inter-layer
cross-talk becomes smaller than a signal band ($1/b_{max} -$
 $1/b_{min}$), whereby the inter-layer cross-talk can be
removed by using a filter or AGC (auto gain control).

Now, the degradation of the optical resolution,
20 i.e., the degradation of the signal modulation degree is
calculated from the optical theory.

In the light receiving optical system shown in
Fig. 1, optical property functions (OTF) $H_0(S)$ and $H_1(S)$
on the plane of a target layer subjected to recording and
25 reproduction and on the plane of an adjacent layer spaced
therefrom by an optical distance d [μm] are indicated by
lines 13 and 14, respectively. The abscissa corresponds
to a repetition frequency S of an object, while the

1 ordinate corresponds to its modulation degree
($H(S)/H(0)$), where S represents a normalized spatial
frequency. Namely, the following equation is satisfied:

$$S = \lambda \times fF/(2\pi a) = \lambda/NAF \times b \quad (\text{Equation 20})$$

5 The optical property function $H_0(S)$, when no
out-of-focus or aberration is observed, is as indicated
by a line 13. In this case, the cut-off frequency at
which the optical resolution is zero is $S=2$. In an
actual recording/reproducing apparatus, since noise
10 components such as laser noise and amplifier noise are
included and the optical system itself has aberration
other than out-of-focus, it is difficult to detect the
cycle b corresponding to the cut-off frequency S equal to
2. Therefore, a half of the modulation degree (-6dB) is
15 determined to be a tolerable value therefor. At this
time, the cut-off frequency S is 1, and a minimum
repetition b_{\min} is defined for the cycle b .

$$b_{\min} = \lambda/NAF \quad (\text{Equation 21})$$

On the other hand, for the optical property
20 function $H_1(S)$ when out-of-focus, the amount of which is
equal to the inter-layer distance d , occurs, a maximum
repetition b_{\max} is defined for the cycle b from $S=2$ at
which $H_1(S)=0$ stands.

As the out-of-focus amount d increases, the
25 optical property function $H_1(S)$ changes in the direction
indicated by an arrow 15, and b_{\max} can also be made
larger.

Thus, frequency components of cross-talk from

1 adjacent layers are not more than f_{min} ($= 1/b_{max}$), so
that such cross-talk components can be absorbed by using
an auto gain control circuit which has a follow-up
characteristic as shown in Fig. 4B.

5 Some numerical examples will be shown below.

The relationship between the out-of-focus
amount d and an amount B_1 of wave front aberration is
expressed by the following equation:

$$B_1 = -d/2 \times (NAF)^2$$

10 As a numerical example, the cut-off frequency S for the
out-of-focus d is calculated, and further b_{max} is
calculated from the cut-off frequency S as follows:

When $d = 6.7 \mu m$, $b_{max} = 4.7 \mu m$; and

$$B_1 = -\lambda$$

15 When $d = 10 \mu m$, $b_{max} = 7.9 \mu m$; and

$$B_1 = -1.5\lambda$$

Also, $b_{min} = (\lambda/NAF) = 1.42 \mu m$.

For example, when a pit edge recording method
disclosed in a known patent document JP-A-63-53722 is
20 employed for a disc where a 2-7 code, which is a variable
length code, is used in the spot scanning direction, and
a track pitch is constantly equal to $1.5 \mu m$, a
reproducible minimum bit pitch q (μm) and the inter-layer
distance d are calculated. As shown in Fig. 4C, a
25 minimum pattern repetition cycle is calculated as
follows:

$$3q = b_{min} = 1.42 \mu m$$

$$q = 0.47 \mu m$$

1 Here, a maximum pattern repetition length is $8q$: $8q=3.76$
 $\mu\text{m} \leq b_{\text{max}}$.

Also, for the cycle of marks formed in the radial direction of the disc, it is necessary that the
5 track pitch is $1.5 \mu\text{m}$ (constant) and $1.5 \mu\text{m} \leq b_{\text{max}}$ is satisfied. Therefore, $d \geq 5 \mu\text{m}$ is sufficient.

Next, a third method will be shown for achieving the foregoing item (3). Although in the second method, the frequency components of inter-layer cross-
10 talk noise are f_{min} or less, signals from a target layer suffer from fluctuations due to variations in local optical property change in certain modulation methods. The 2-7 modulation code employed in the foregoing example is also one of such cases. The power spectra character-
15 istic of this modulated signal is shown in Fig. 4A. It can be seen from Fig. 4A that the signal has slight components below f_{min} . These components can be suppressed by a filter circuit and an AGC circuit, as described above. Even without these circuits, however,
20 inter-layer cross-talk noise can be suppressed by removing variations in local optical property change and making direct current components constant. The principle of the third method is based on the employment of a code which defines that a total area occupied by local optical
25 changes (marks) included in the area defined by the spot diameter ($2d \times \text{NAF}$) on an adjacent layer is constant. By employing this code, an amount of inter-layer cross-talk included in a reproduced signal when scanning a spot

1 presents a constant value in direct current. The third
method may be used together with the first method.

An example will be shown. A power spectra 87
of a modulated signal when employing an EFM (Eight to
5 Fourteen Modulation) modulation method described in a
known literature "Digital Audio", pp 322-324, by
Toshitada Doi and Akira Iga, presents a feature that the
spectra of low range components abruptly falls as shown
in Fig. 4A. Therefore, the inter-layer distance d may be
10 set such that a turning point 88 from which the spectra
abruptly falls coincides with the cut-off frequency at
which the optical property function $H_1(s)$ becomes zero in
an adjacent layer.

For example, assuming that $q = 0.6 \mu\text{m}$, $2.82q =$
15 $1.7\mu\text{m} \geq b_{\text{min}} = 1.42 \mu\text{m}$, and $10.36q = 6.2 \mu\text{m} \leq b_{\text{max}}$, where
the repetition cycle at the turning point 88 is $24 \mu\text{m}$,
and the inter-layer distance d is $22 \mu\text{m}$. At this time,
an occupying ratio of marks included in an area defined
by the spot diameter ($2d \times \text{NAF} = 24 \mu\text{m}$) on the adjacent
20 layer is maintained to be approximately 50%, whereby
components of a reflected light amount from the adjacent
layer included in a detected reproduced signal always
presents a constant value.

In Figs. 21 and 22, the present invention is
25 applied to a case where two-dimensional recording is
performed within layer planes. As shown in Fig. 21, the
two-dimensional recording/reproducing method employs, for
example, four points arranged in a 2×2 lattice as one

1 block to represent $2^4 = 16$ data by a combination of four
bits which are marks on the four lattice points, thereby
achieving high density recording. The two-dimensional
recording can be implemented by the first and second
5 methods. Further, as shown in Fig. 22, it is required
that the same number of marks (one in Fig. 22) is
included in lattice points within each 4×4 lattice
block. If more lattice blocks are included in the spot
area ($2d \times NAF$) on an adjacent layer, the number of marks
10 included in the spot and accordingly the area occupied by
the marks are substantially constant, whereby the third
method can be applied thereto.

Incidentally, in an optical disc, a light spot
at the diffraction limit is formed on the plane of each
15 recording layer. In each optical system shown in Fig. 2,
if an out-of-focus of a certain value dm occurs,
conditions of a focusing system of a microscope are
satisfied, whereby an image on a recording layer plane
may be formed on a light receiving plane. For example,
20 when a target layer receives light formed into a spot at
the diffraction limit, and a distance from the target
layer to another layer is dm , a mark string pattern on
this target layer is formed on the light receiving plane,
whereby cross-talk noise in a signal band may be added to
25 information signals on the target layer. It is therefore
desirable to design the disc structure such that the
inter-layer distance does not coincide with dm .

Also, since recording layers are irradiated

1 with the same light, if the inter-layer distance is as
short as an inteferable distance, lights reflected from
the respective recording layers interfere with each
other. As a result, cross-talk noise between layers
5 cannot be expressed by a ratio of a received light amount
on the target layer to a received light amount on other
layers on the light receiving planes. Stated anther way,
since interference occurs, inter-layer cross-talk noise
appears in the form of the square root of the received
10 light amount ratio in the worst case. It is between
adjacent layers when this influence actually causes
problems.

An embodiment intended to solve this problem is
shown in Fig. 27. The principle of this embodiment lies
15 in that the polarization direction of the light reflected
from an adjacent layer is changed to prevent inter-
ference. As a means for changing the polarization
direction, a disc shown in Fig. 27 is provided with a
wave plate layer 201 in each intermediate layer 2. A
20 quarter wave plate layer 201 deviates the phase
difference of waves in an electric field generated by
travelling lights by an angular distance of 90° with
respect to the depth direction of the layers. Stated
another way, the difference in optical thicknesses in two
25 directions is changed by a quarter wavelength portion.
By providing a disc with such a structure, assuming that
the polarization direction of an emitted light is E-
polarization, lights reflected from layers adjacent to

1 each other are different in phase by a difference
produced by reciprocating the quarter wave plate layer,
i.e., a half wavelength or a 180° -phase portion, whereby
the polarization direction crosses alternately with E-
5 polarization and H-polarization. For this reason,
reflected light components between adjacent layers do not
interfere with each other, so that cross-talk noise
between these layers can be expressed by a simple
received light amount ratio on the light receiving plane,
10 with the result that cross-talk between layers can be
reduced. Further, a polarization beam splitter 202 is
inserted in the optical system, as shown in Fig. 27, to
separately employ detector 203 or 204 depending on the
polarization direction of a reflected light. Since this
15 structure prevents a reflected light from being detected
from adjacent layers, a tolerable value for variations of
the size of the optical detectors can be set to a larger
value in the foregoing first reproduction method.

Next, description will be made as to an
20 apparatus for achieving the principle of the three-
dimensional recording/reproducing method of the present
invention shown in the foregoing section (1).

(2) Three Dimensional Disc Format and Data Management

Fig. 5A shows an exemplary format of the multi-
25 layer disc 4. The layers are numbered from 1 to n from
the base 3 to which the light is incident toward the
progressing direction of the light. Fig. 5B shows a data
format on a k_{th} layer, where m represents a sector which

1 radially divides the disc, and l represents a track for
managing a data position in the radial direction. Data
is managed by the three addresses (l, m, k). The format
on an arbitrary track l and a sector m comprises a
5 preformat area in which a timing for recording/
reproduction and address information have previously been
stored, and data area for recording/reproducing user data
and recording and managing a variety of management data
such as the presence or absence of data, read-out
10 inhibition, and so on, as shown in Fig. 5C. The disc is
also provided, in addition to the layers for recording/
reproducing user data, with a ROM (Read Only Memory)
layer or a WOM (Write Once Memory) layer which permits an
OS (Operating System) of an upper level controller or
15 recording or reproduction conditions on each layer, as
will be later described, to be preformatted upon
producing the disc or recorded thereon at the time of
shipment. Also, as a management layer for data written
on the user layers, data conditions of each layer, e.g.,
20 the presence or absence of data, error management, an
effective data area, and the frequency of overwrite may
be recorded on the ROM layer at any time. It may also be
used as an exchange layer such that data can be recorded
thereon and reproduced therefrom in place of a layer
25 where a recording error is detected.

The order of data recording includes, for
example, the following combinations (a) - (e).

(a) Recording is performed sequentially from the top

1 layer, i.e., $1_{st} - k_{th} - N_{th}$ layers. It should be noted
that recording proceeds to the next layer after all user
sectors and tracks have been filled with information in
each layer.

5 When this type of data recording is performed,
a recording medium which has the characteristic of
increasing the transmissivity after recording may be used
to carry out further reliable recording/reproduction.
Specifically, since the transmissivity up to the lower-
10 most layer increases, light with an intensity substan-
tially equal to that necessary to record on the top layer
can provide a lower target layer with a sufficient light
intensity required for recording thereon. Also upon
reproduction, since reflected light components from the
15 target layer returns to the detector substantially
without being attenuated, a reproduced signal with a high
SN ratio is generated. A recording medium having the
above-mentioned characteristic is, for example, a
perforation recording medium. When recording is
20 performed on this medium, a reflection layer thereof is
perforated, thereby decreasing the reflectivity, i.e.,
increasing the transmissivity.

(b) Recording is performed sequentially from the
lowermost layer, i.e., $N_{th} - k_{th} - 1_{st}$ layers. The rest of
25 the operation is the same as the order (a).

(c) Although recording proceeds to the next layer after
information has been recorded on all user sectors and
tracks of each layer, a layer to be recorded is accessed

1 at random.

(d) Although layers to be recorded are accessed at random, after data has been recorded on a particular sector in a layer, the same sector in the next layer is
5 filled with data. After the same sector in all the layers has been full, data is recorded on the next sector.

(e) On a particular track, random access is performed in the layer direction. In this case, a variable length
10 block, which is a data management for magnetic disc, not a fixed block management based on the sector, is applied to correspond cylinders of a magnetic disc to the layers, whereby a data format for the magnetic disc can be applied as it is to the recording medium of the present
15 invention.

In the random access, the information recording area is managed by an upper level controller or the foregoing management area, for example, so as to prevent a recorded area from being erroneously accessed upon
20 recording.

(3) Whole Arrangement of Apparatus

Fig. 6 shows the whole arrangement of a three-dimensional recording/reproducing apparatus. When recording, user data 17 is supplied to a modulation
25 circuit 18 to generate modulated binary data 19. The modulated binary data 19 is passed to a recording condition setting circuit 20 which drives a laser driving circuit 21 so as to modulate the intensity under optimal

1 recording conditions at a position at which a light spot
is positioned. Then, the laser driving circuit 21
modulates the intensity of light emitted from a semi-
conductor laser disposed in an optical head 22 to record
5 user data on a disc 4.

Conversely, when previously recorded data is
reproduced, a light spot is located at a track position
on a target recording layer on the disc 4, a feeble light
is irradiated thereon, and an intensity change of a
10 reflected light is converted by a photo detector 10 to an
electric signal to generate reproduced signals 23, 24.
The reproduced signals 23, 24 are passed through a
reproduction control circuit 25 to suppress inter-layer
cross-talk, and then supplied to an AGC (auto gain
15 control) circuit 26 to absorb fluctuations of low
frequency components which are lower than a data band to
conform the signals to an absolute level which is
processed by subsequent circuits.

Thereafter, the reproduced signals are passed
20 to a waveform equalizer 27 to correct distorted waveform
(deterioration of amplitude, phase shift, etc) by using a
data pattern, and converted to binary signals by a shaper
28. The shaper 28 may be one which converts a signal to
a binary code by slicing the amplitude, or one which
25 detects zero-cross by differentiation.

The binary signals are next passed to a phase
synchronization circuit 29 where a clock is extracted
therefrom. The phase synchronization circuit 29 is

1 composed of a phase comparator 30, a low pass filter
(LPF) 31 and a voltage control oscillator 32. The binary
signals are passed to an identifier 33 which determines
whether a data bit is "1" or "0" by using the clock
5 extracted by the phase synchronization circuit 29, and
converted to user data 17 by a decoder 34. In the
foregoing recording/reproducing processes, if the light
spot is located on a target layer and at a target
position on the target layer by an instruction from an
10 upper level controller, an out-of-focus signal and a
track shift signal from the optical head 22 are detected
by a detector 35, an appropriate signal for servo control
is generated by a compensation circuit 36, and a light
spot positioning mechanism is driven by a driving circuit
15 37.

(4) Access Method

The optical spot positioning mechanism may be a
two-dimensional actuator which drives a focus lens in the
layer direction and the radial direction of the disc or a
20 combination of a one-dimensional actuator which drives
the focus lens 8 only in the layer direction and a
galvano mirror for deflecting light flux incident to the
focus lens 8 to the radial direction of the disc.

Here, for a case where random access is
25 performed to record and reproduce data, as described in
Section (2), a method of firstly focusing on a target
layer k will be described. Since the size of a reflected
light spot from the target layer changes due to out-of-

1 focus, a detection of an out-of-focus signal can employ a
front-to-rear differential out-of-focus detecting method
disclosed in a known document "JP-A-63-231738 and JP-A-1-
19535." Fig. 24A shows an AF error signal 35 generated
5 when the position of the focus lens 8 is shifted in the
layer direction Z with respect to the disc plane. It can
be seen from Fig. 24A that an out-of-focus error signal
from each recording layer and a zero-cross point 105
which represents a focused point are generated in order.
10 Fig. 23 shows a block diagram of the first
embodiment when a target k_{th} layer is accessed. For the
rotating disc 4, a saw-tooth wave 106 is generated by an
AF (autofocus) actuator shift signal generating circuit
93 to drive an AF actuator driver 91, thus shifting the
15 focus lens 8 in the +Z direction (direction in which the
lens is approached to the disc) with respect to the disc
plane. At this time, an AF detecting circuit 89
generates the AF error signal 35. From this signal, the
zero-cross point 105 is detected by a withdraw point
20 determination circuit 92, thereby informing an AF servo
system controller 99 of a focused point on the surface of
a certain recording layer. The determination circuit
generates an AF pulse 37 as shown in Fig. 24B by a slice
level 37 which is slightly shifted from a zero slice
25 level, and a falling edge of the AF pulse 37 is detected
to supply the controller 99 with a timing immediately
before the lens 8 passes a focused point.

The controller 99 recognizes a focus withdraw

1 state by an instruction from the upper level controller,
and changes over a switch 97 at the time the timing is
inputted to connect an AF servo circuit 90 to the AF
actuator driver 91 to close the servo loop. In this
5 state, the AF servo circuit 90 drives the AF actuator
such that the AF error signal is always zero. Thus, a
spot at the diffraction limit can be stably formed on a
layer even if the disc 4 swings when rotating.

Next, a layer number detecting circuit 95 reads
10 a layer address recorded on the preformat area shown in
Fig. 5C to recognize the number of a layer on which the
focus is placed, and sends the number to the AF servo
system controller 99. The controller 99 recognizes in
which of upward or downward direction (+ or - ($k-j$)) and
15 how many layers ($|k-j|$) the spot should jump from a j_{th}
layer on which the spot is now focused to a k_{th} target
layer instructed by the upper level controller, and has a
layer jump signal generating circuit 96 generate a jump
force signal 107 which in turn is inputted to the AF
20 actuator driver 91. The jump signal 107 is composed of a
pair of positive-polarity and negative-polarity pulses
per one-layer jump, and replaces the positive or negative
pulse in accordance with the upward or downward jumping
direction. The first pulse is used to drive the spot
25 approximately by a jumping distance in the jumping
direction, and the next polarity inverted pulse is
provided to prevent the spot from excessively jumping. A
number of pairs of pulses equal to the number of layers

1 over which the spot is to jump is inputted to the driver
91. Next, the layer number is detected, and when j
becomes equal to k , the spot is positioned on the k_{th}
target layer. When another layer is to be accessed by
5 random access, the layer jump may be executed similarly
to the above.

Fig. 25 shows a block diagram of a second
embodiment when a k_{th} target layer is accessed.

A focus lens 8 is raised or lowered relative to
10 a rotating disc 4. At this time, the foregoing AF error
signal is generated. Also, a total light amount 36
detected by a photo detector 10 and outputted from a
total light amount detecting circuit 102 has a peak value
when the focus is placed on each recording layer, as
15 shown in Fig. 24A. Therefore, a pulse generating circuit
98 in a cross layer signal detecting circuit 101 detects
an AF pulse 37 and a total light amount pulse 38 by slice
levels 103, 108, and the total light amount pulse 38 is
used as a gate to detect falling edges of the AF pulse,
20 thereby further reliably detecting a focused point.

Moreover, to recognize the direction in which the lens is
shifted relative to the disc, the cross layer pulse
generator 99a generates from these two kinds of pulses an
up pulse P_a 109 and a down pulse P_b 110 which are counted
25 to always recognize on which layer the lens is located.

In Fig. 25, a saw-tooth wave 10b is generated
from the AF actuator shift signal generating circuit 93
to shift the AF actuator, resulting in shifting a focused

1 position from the top layer to the lowermost layer of the
disc. At this time, if a shifted amount is sufficiently
larger than a vertical swinging amount of the rotating
disc, the operation of the AF actuator is ensured.

5 Focused points on N layers are counted by the cross layer
signal detecting circuit 101, and the top layer ($n = 1$)
and the lowermost layer ($n = N$) are recognized from an
upper limit of the up pulse 109 when the lens is shifted
upwardly and a lower limit of the down pulse 110 when the
10 lens is moved downwardly, respectively. A switch 100 is
changed over by an instruction from the upper level
controller immediately before the focus is placed on the
next target layer to close the servo loop. Such a
control allows layers to be accessed without providing a
15 layer address.

Incidentally, when using a medium whose
transmissivity and reflectivity change upon recording
information, the AF error and total light amount signals
123, 124 are different from those shown in Fig. 24 in the
20 vicinity of a recorded layer as shown in Fig. 26B. This
indicates that a light amount changes when the spot scans
a portion where exist marks, and returns to a normal
value when the spot passes a portion without marks.
Since the signal thus fluctuates, even a signal in a
25 servo band also deteriorates to give rise to fluctuations
of a gain in the AF servo system and AF offset, which
results in out-of-focus on a recorded layer. In such a
case, by always holding a signal indicating a portion

1 without marks in signal components detected by the photo
detector, the ideal AF error signal 35 and total light
amount signal 36 are provided.

5 An exemplary means for implementing this method
is shown in Fig. 26B. Fig. 26B specifically shows the AF
detecting circuit 89 and the total light amount detecting
circuit 102 in Figs. 23 and 25, respectively. Front and
rear photo detectors 111 and 112 in the drawing
illustrating the principle of a front-to-rear differ-
10 ential AF error signal detecting optical system comprise
light receiving planes 119, 120 or 121, 122. If the
sizes of spots 113, 114 are equal on the front and rear
photo detector planes 111, 112, it indicates a focused
point. Sum signals of the respective detectors are
15 generated by preamplifiers 115, 116 which have a band in
which the spot scans strings of marks, i.e., a data
recording/reproducing frequency band. Next, signals in a
scanned mark portion are detected by sample and hold
circuits 117, 118 and held therein during a period of a
20 servo band. A difference signal of the thus generated
signals is derived as the AF error signal 36, while a sum
signal of them is derived as the total light amount 36.
The sample and hold circuits 117, 118 may be a peak hold
type which samples a maximum point of a light amount.
25 Alternatively, an area in which no mark is recorded is
previously provided as a sample area in a format, and the
sample and hold circuits 117, 118 may recognize such a
sample area by a sample timing bit and hold a signal in

1 that area.

Although in this embodiment, a front-to-rear differential method has been shown as an out-of-focus detecting method, another out-of-focus detecting method
5 such as an astigmatism method or an image rotating method may be employed.

After accessing a target layer, a positioning in the radial direction of the disc, i.e., track positioning is performed on that target layer. A track
10 shift signal can be detected by a known push-pull method by providing each layer with a guide groove 39 as shown in Fig. 20. In this method, since diffracted lights from grooves other than the target layer are out of focus, the phase of light wave striking the grooves is disordered so
15 that a uniform light distribution is present on the photo detector, whereby no influence is exerted on the track shift signal about the target layer. Also, as shown in Fig. 22, if wobble pits 40 are previously formed on each layer in the track direction, a known sample servo method
20 can be applied. The above described spot positioning technique is disclosed in known patent documents JP-A-63-231738 and JP-A-1-19535. A method of forming guide grooves and wobble pits will be later described.

(5) Recording Control Method

25 Next, description will be made as to a recording control method which achieves the principle of the three-dimensional recording method of the present invention shown in Section (1). As described in Section (1),

1 in order to stably record on a k_{th} layer or a target
 layer, a recording power P (light intensity) must be
 determined in consideration of the transmissivity up to
 the k_{th} layer. Thus, as shown in Fig. 6, the recording
 5 condition setting circuit 20 employs address recognition
 42 and the transmissivity 42 up to the target k_{th} layer.
 An example of this circuit is shown in detail in Fig. 7
 in a block form, and examples of signals are illustrated
 in Fig. 9.

10 Referring to Fig. 9, when binary data 19 is
 recorded as recording marks 43, recording conditions for
 the address recognition 41 (l, m, k), for example,
 setting of recording pulse width, recording power setting
 condition and so on are previously stored in ROMs 44, 45
 15 in consideration of the difference in recording condi-
 tions due to a recording position and a recording state
 by a data pattern, whereby a light intensity modulation
 signal $P(t)$ 47 is generated corresponding to the output
 of a D/A convertor 46, and accordingly the marks in an
 20 ideal recording state can be recorded. Such a circuit
 arrangement indicated by solid lines in Fig. 7A can be
 applied to the following case.

When the foregoing Section (2) item (b) is
 employed as the order of recording data, or when the
 25 third method for achieving (1) item (2) and Section (2)
 item (a) are employed, since the transmissivity 42 up to
 a target layer ($\sum T_n$ ($n=1, 2, \dots, k-1$)) has been
 determined upon producing the disc, if a layer address k

1 is inputted, the transmissivity is handled as a known
value.

In the cases other than the above, the
transmissivity up to a target layer is not known at the
5 time of recording. To coop with this, circuits (47, 48)
indicated by broken lines in the circuit of Fig. 7A are
added. The power setting ROM 46 has been loaded with
recording power setting values in consideration of the
transmissivity up to a k_{th} layer when an all-layers unused
10 state.

The transmissivity up to the k_{th} layer $\sum T_n$ ($n=1,$
2, ..., $k-1$) upon shipment of the disc (or a design
value) derived by the address recognition 42 and a
transmissivity up to the k_{th} layer $\sum T_n'$ ($n=1, 2, \dots, k-1$)
15 42 immediately before recording, detected by a method,
later referred to, are inputted to a division circuit 47,
while a change G in transmissivity is inputted to a gain
control circuit 48, so as to set an optimal recording
power.

20 An example to which this circuit arrangement
can be applied will be shown. Suppose that "the manage-
ment layer for layer data" described in Section (2) is
provided and its contents have previously been reproduced
for recognition, the third method for achieving Section
25 (1) item <3> is applied, and the data management referred
to in Section (2) items (c), (d) is implemented. If a
layer on which recording is in progress is known, the
transmissivity up to the k_{th} layer $\sum T_n'$ ($n=1, 2, \dots, k-1$)

1 42 can be derived since the transmissivity of each layer
after recording in a light spot is constant and known.

Another example is a method of previously
scanning the spot to detect a change G in transmissivity.

5 As the method of previously reproducing an area
on which recording is to be performed, after a reproduc-
tion check is done in the first rotation of the disc in a
recording mode, recording is performed in the next
rotation, and then a recording error check is done in the
10 third rotation. Another method is one which employs a
plurality of spots as shown in Fig. 8 and performs a
reproduction check by a preceding spot 49. Here, the
latter method is explained as an example. The reproduc-
tion check employs a reproduced signal $C'k(t-\tau)$ derived
15 by the preceding spot 49, where τ represents the distance
between the preceding spot 49 and a recording spot 51
converted into a time. Then, the transmissivity change G
is calculated by a processor 52 as a square root of a
ratio of a reproduced signal Ck' in a state where the
20 spot is focused on the target k_{th} recording layer to a
reproduced signal Ck as a design value which has
previously been set upon shipment of the disc, as shown
in Fig. 7B. This calculation is performed because the
signal is reproduced by using a reflected light, so that
25 a change in transmissivity up to the k_{th} layer appears in
the reproduced signal in the form of its square.

It should be noted however that the value of
the reproduced signal Ck can be detected by previously

1 providing a non-recording area with respect to the layer
direction on a disc plane, as a check area in a disc
format, and absorbing variations among different discs
and optical variations in a disc. A highly accurate
5 recording power control is thereby achieved. The photo
detector 10 for generating reproduced signals may be
formed in the shape of Fig. 1, as has been described in
connection with the first method for satisfying the
condition in Section (1) item <3>, to reduce the
10 influence of lights reflected from other layers, whereby
reflected light components only from the target layer can
be detected as reproduced signal so that the trans-
missivity change G can be further accurately derived.
Although a recording state 53 when gain control is not
15 performed is different from the ideal recording state 47
as shown in Fig. 9, the ideal recording state 47 can be
achieved by performing a gain control for the recording
power and recording with $G \times P(t)$.

(6) Reproduction Control Method

20 Next, the reproduction control circuit 25 shown
in Fig. 6 will be described in detail with reference to
the accompanying drawings. Here, in addition to the
principle of reproduction for reducing inter-layer cross-
talk by the first to third methods shown in Section (1),
25 a fourth method will be shown for suppressing inter-layer
cross-talk components in a data signal band which may
arise when an inter-layer distance is further reduced in
order to achieve a higher recording density or inter-

1 layer cross-talk components which may arise when the
optical system is shifted from an ideal state. The
fourth method, in addition to the detection of reflected
light components from a target layer as shown in the
5 first method, detects reflected light components from
adjacent layers which particularly include a majority of
inter-layer cross-talk, and removes components mutually
included in those detected by these two methods by a
calculation to extract reflected light components of the
10 target layer.

Fig. 17A shows the principle of the optical
system employed in the fourth method. Although the basic
configuration is the same as that shown in Fig. 1, photo
detectors 54, 55 are further positioned on focal planes
15 of adjacent layers $(k + 1)$, $(k - 1)$ on the light receiving
plane side when the focus is placed on a k_{th} layer.
However, since the photo detectors 54 and 55 disposed as
shown in Fig. 17A mutually shield the light, half mirrors
56, 57 are inserted in the focus system. Alternatively,
20 beam splitters may be inserted in place of the half
mirrors as shown in Fig. 17B. The shape of the photo
detectors 10, 54 and 55 is determined to be a circle, the
diameter of which is $D = (\lambda/NAI)$. Also, pinholes may be
used to implement these detectors as shown in Fig. 17C.
25 Reproduced signals detected by the respective photo
detectors in this arrangement are shown in Fig. 14.

Fig. 14 shows a reproduced signal C_k detected
by the photo detector 10; a reproduced signal $C(k - 1)$

1 detected by the photo detector 55; and a reproduced
 signal $C(k + 1)$ detected by the photo detector 54. These
 reproduced signals are generated by a circuit shown in
 Fig. 13. It should be noted that if a system shown in
 5 Fig. 17 is employed, integration circuits 59, 60 and
 delay circuits 61, 62 shown in Fig. 13 are not necessary.
 As shown in Fig. 14, when the distance between adjacent
 layers is shorter than the distance between an adjacent
 layer which satisfies the first - third methods and a
 10 target layer, a reproduced signal 73 without inter-layer
 cross-talk which is derived when a spot 69 scans a mark
 string 71 on a k_{th} layer fluctuates as a reproduced signal
 72. This is because, as the spot 69 scans on the k_{th}
 layer, components of a reproduced signal 64 detected from
 15 the $(k-1)_{th}$ adjacent layer by a spot 70 defocused on the
 $(k-1)_{th}$ adjacent layer which scans a mark array 74 on the
 $(k-1)_{th}$ adjacent layer, and components of a reproduced
 signal 63 likewise detected from the $(k+1)_{th}$ adjacent
 layer on the opposite side in the Z-direction are
 20 included in an unneglectable degree with respect to the
 reproduced signal 73. For this reason, the following
 equation is calculated by a calculation circuit 66 as
 shown in Fig. 13.

$$\begin{aligned}
 C_k &= C_k R + \beta \times C(k - 1)R + \beta \times C(k + 1)R \\
 25 \quad C(k - 1) &= C(k - 1)R + \beta \times C_k R + \beta \times C(k - 2)R \\
 C(k + 1) &= C(k + 1)R + \beta \times C_k R + \beta \times C(k + 2)R
 \end{aligned}$$

(Equation 22)

where $C_n R$ represents reproduced signal components by a

1 reflected light only from an n_{th} layer.

In Equation 22, $\beta < 1$ is satisfied. From the above equation:

$$\text{Calculation } F \equiv C_k - \gamma \times C(k-1) - \gamma \times C(k+1)$$

$$\begin{aligned} 5 \quad & \equiv C_k R + \beta \times C(k-1)R + \beta \times C(k+1)R \\ & - \gamma \times \{C(k-1)R + \beta + C_k R + \beta \times C(k-2)R\} \\ & - \gamma \times \{C(k+1)R + \beta \times C_k R + \beta \times C(k+2)R\} \\ & \quad \quad \quad (\text{Equation 23}) \end{aligned}$$

Since $C(k-2)R$ and $C(k+2)R$ are sufficiently
10 small and frequency components are also low, these terms can be neglected.

$$\begin{aligned} \text{Thus, } F & \equiv (1 - 2\gamma\beta) \times C_k R + (\beta - \gamma) \times C(k-1)R \\ & + (\beta - \gamma) \times C(k+1)R \end{aligned}$$

(Equation 24)

15 Here, if $\gamma \equiv \beta < 1$,

$$F \equiv (1 - \beta^2) \times C_k R \quad (\text{Equation 25})$$

whereby the inter-layer cross-talk can be suppressed, and the reproduced signal 68 after being processed coincides with the reproduced signal 73 as shown in Fig. 14. As an
20 alternative arrangement for achieving the foregoing fourth method, an example of employing a plurality of spots is shown below. Referring again to Fig. 14, a spot 75 having the same spot diameter as the defocused spot 70 scans the two adjacent layers $(k-1)$ and $(k+1)$ prior
25 to the spot 69 to detect signals to be reproduced. Note that delay circuits 61, 62 corresponding to spot intervals are inserted, as shown in Fig. 13, to perform calculations similar to the above. An example of an

1 optical system used in this arrangement is shown in Fig.
18. Referring to Fig. 18, an optical axis is shown for
three separate cases in order to illustrate the principle
of the optical system. This principle is applicable also
5 to an optical system employing a focus lens 8. A means
for setting the spot diameter of a spot 75 which is
focused on the upper adjacent layer and a spot 82 which
is focused on the lower adjacent layer to $(2d \times NAF)$ may
be a diaphragm 83 inserted as shown in Fig. 18 to reduce
10 an effective aperture. More specifically, an effective
diameter a' may be changed to $\lambda/(2d \times NAF^2) \times 2$. Of
course, similar effects can be produced if the numerical
apertures of the focus lenses for the two preceding spots
are reduced. That is, $NAF' = \lambda/(2d \times NAF)$ is employed.
15 While the shape of the preceding spot 75 is
hitherto the same as the spot shape 75 shown in Fig. 14
(i.e., the same shape as that of the spot 70), a spot
shape 76 shown in Fig. 15 (an elliptical shape oblonger
than the spot 75) or three spots 77, 78 and 79 shown in
20 Fig. 16, by way of example, can produce similar effects.
For employing these spots, integration circuits 59, 69
are inserted in the circuit of Fig. 13. Referring to
Fig. 15, if a reproduced signal detected by the preceding
spot is multiplied with a weighting function 80 derived
25 by approximating a Gaussian distribution, which is an
intensity distribution of the spot, to, for example, a
triangle distribution and integration is performed to
this product, a reproduced signal when the spot 75 is

1 scanning the mark string 74 can be effectively derived.
As to the spots shown Fig. 16, a weighting function 81
may be similarly employed in consideration of a spot
intensity distribution in the two-dimensional direction.

5 Now, description will be made as to a method of
calculating β in a weight setting circuit 67 used in the
calculation circuit 66 shown in Fig. 13. If mark record-
ing areas on at least three layers including upper and
lower adjacent layers are located as a disc format such
10 that they are not included in the same light flux, as
shown in Fig. 19, $h(k-1)/h_k$ and $h(k+1)/h$ are set to
 $\beta(-1)$ and $\beta(+1)$ as shown in Fig. 14, whereby weights for
the upper and lower adjacent layers can be derived.

While in the embodiments so far described,
15 description has been made as to a case where recording/
reproduction is performed basically on a single layer, it
is also possible to simultaneously recording/reproducing
on two or more layers by using a plurality of spots and
focusing these spots on each layer. In other words,
20 parallel recording/reproduction is enabled, whereby a
data transfer rate can be increased. A means for forming
a plurality of spots may be a plurality of optical heads
22 which are located on a single disc or a single head
having a plurality of light source incorporated therein.
25 Also, by employing light sources which generate lights
having different wavelength from each other as a
plurality of light sources, a recording layer to be
recorded can be selected by a wavelength, and separate

1 reproduction is also enabled by a wavelength filter.

(7) Embodiment of Disc Structure and Disc Producing
Method

On the surface of a disc-shaped chemical
5 tempered glass plate having a diameter of 130 mm and a
thickness of 1.1 mm, a replica substrate 401 is produced
by a photo polymerization method (2P method). Formed on
the replica substrate 401 is a UV cured resin layer
having tracking guide grooves at intervals of 1.5 μm and
10 prepits (referred to as a header section) in the form of
uneven pits in elevated portions between grooves at the
start of each of 17 sectors formed by equally dividing
the disc plane for representing layer addresses, track
addresses, sector addresses and so on.

15 The structure of the disc will be explained
with reference to Fig. 11. On the replica substrate 40,
an antireflection film 402 made of silicon nitride (SiN)
was formed in a thickness of about 50 nm by using a
sputtering apparatus which provides good uniformity and
20 reproductivity of film thickness. Next, a recording film
403 composed of $\text{In}_{54}\text{Se}_{43}\text{Tl}_3$ was formed in a thickness of 10
nm in the same sputtering apparatus. On this recording
film 403, a UV cured resin layer 404 having tracking
guide grooves and prepits representing layer addresses,
25 sector addresses, track address and so on was formed in a
thickness of 30 μm in consideration of a heat insulation
effect associated with other layers by the 2P method
which uses a transparent frame such that the light is

1 incident from the frame side.

Subsequently, an SiN antireflection film 405 was formed in a thickness of about 50 nm in the sputtering apparatus, and on this layer a recording film 406
5 composed of $\text{In}_{54}\text{Se}_{43}\text{Tl}_3$ was formed in a thickness of 10 nm. Further on this film a UV cured resin layer 407 having tracking guide grooves and prepits representing layer addresses, sector addresses, track address and so on was formed in a thickness of 30 μm by the 2P method. Further
10 on this layer, an SiN antireflection film 408 of silicon nitride was formed in a thickness of about 50 nm in the same sputtering apparatus, and a recording film 409 composed of $\text{In}_{54}\text{Se}_{43}\text{Tl}_3$ was formed in a thickness of 10 nm on this antireflection film 408.

15 In the same manner, an SiN antireflection film 402'; an $\text{In}_{54}\text{Se}_{43}\text{Tl}_3$ recording film 403'; a UV cured resin layer 404'; an antireflection film 405'; an $\text{In}_{54}\text{Se}_{43}\text{Tl}_3$ recording film 406'; a UV cured resin layer 407'; an SiN antireflection film 408'; and an $\text{In}_{54}\text{Se}_{43}\text{Tl}_3$ recording film
20 409' were sequentially formed on a like replica substrate 401'. The two discs thus produced were bonded by a bonding agent layer 410 with the layers 409 and 409' being directed inwardly. The thickness of the bonding agent layer is about 50 μm . The disc thus produced
25 allows recording/reproduction to be performed on a single disc from both sides.

While in the foregoing example of the disc production, guide grooves 39 for push-pull tracking has

1 been explained, the wobble pits 40 used for a sample
servo method can be likewise formed by a similar method
to that for forming the prepits.

The disc produced in this embodiment is such
5 that a change in atomic arrangement of atoms constituting
the recording films is caused by irradiation of a laser
light to change optical constants, and data is read out
utilizing the difference in reflectivity. The change in
atomic arrangement refers to a phase change between
10 crystalline and non-crystalline.

In the disc immediately after forming the
recording films, the recording film constituting elements
are not sufficiently reacted so that the recording films
are in a non-crystalline state. When this disc is used
15 as a Write Once type medium, a recording laser light is
irradiated to the recording films to perform crystalliza-
tion recording. Alternatively, the recording films are
previously heated by irradiation of an Ar laser light,
flash anneal or the like, such that each element is
20 sufficiently reacted and crystallized, and thereafter a
recording laser light with a high power density is
irradiated to the recording films to perform non-
crystallization recording. Here, a range of a laser
power suitable to the crystallization recording should be
25 above a temperature causing crystallization and below a
temperature causing non-crystallization. On the other
hand, when this disc is used as an overwritable type
medium, the recording films are previously heated by

1 irradiating an Ar laser thereto, subjected to flash
anneal or the like to sufficiently react and crystallize
each element, and thereafter, a recording laser light
which is modulated between a laser power suitable for
5 crystallization and a laser power suitable for non-
crystallization is irradiated onto the recording films to
overwrite data thereon.

The disc was rotated at 1800 rpm, the light
(wavelength is 780 nm) from a semiconductor laser
10 maintained at a power level (1 mW) with which recording
was not performed was converged by a lens disposed in a
recording head and irradiated onto a recording film on
the first layer through the substrate, and a reflected
light was detected, thereby driving the head such that
15 the center between the tracking grooves was always
coincident with the center of a light spot. By forming a
recording track between two adjacent grooves, the
influence of noise generated from the grooves can be
avoided. Automatic focusing was performed so as to focus
20 the light spot on the recording film while thus continu-
ing the tracking, to perform recording/reproduction.
When the light spot passed a recording portion, the laser
power was decreased to 1 mW, and the tracking and
automatic focusing was still continued. It should be
25 noted that the tracking and automatic focusing is
maintained also during a recording operation. This
focusing enables the light spot to be independently
focused on the respective recording layers 403, 406 and

1 409 of the disc.

A case where recording was performed sequentially on recording films from the substrate side toward the lowermost layer will be shown, assuming that the disc
5 constructed as described above is rotated at a linear velocity of 8 m/s (rotational speed: 1800 rpm, radius: 42.5 mm). First, the focus was placed on the recording film 403 which was irradiated with a recording pulse with a recording frequency at 5.5 MHz and a period of 90 ns to
10 record on this film 403. A recording power dependency of a reproduced signal intensity at this time is shown below:

	Recording Power (mW)	Reproduced Signal Intensity (mV)
	6	30
15	7	100
	8	160
	9	210
	10	250
	11	280
20	12	300
	14	310

Then, after recording on the recording film 403, the light spot was focused on the recording film 406 to perform recording thereon. A recording power
25 dependency of a reproduced signal intensity at this time is shown below:

1	Recording Power (mW)	Reproduced Signal Intensity (mV)
	7	25
	8	95
	9	155
5	10	205
	11	245
	12	275
	13	295
	15	305

10 After recording on the recording films 403 and 406, the light spot was focused on the recording film 409 to perform recording thereon. A recording power dependency of a reproduced signal intensity at this time is shown below:

15	Recording Power (mW)	Reproduced Signal Intensity (mV)
	8	20
	9	90
	10	150
	11	200
20	12	240
	13	270
	14	290
	16	300

25 Also, the results will be shown below, when, after recording a signal at 3 MHz on the recording film 403, a signal at 4 MHz on the recording film 406 and a signal at 5 MHz on the recording film 409, the light spot

1 was focused on the recording films 403, 406 and 409 to
read reproduced signals therefrom.

The reproduced signals were analyzed by a
spectra analyzer, and, as a measuring condition, the
5 resolution frequency width was selected to be 30 kHz.
The following table shows measurement results of CN
ratios (ratio of noise components to carrier components)
of the reproduced signals at a carrier frequency.

		3 MHz	4 MHz	5 MHz
10	Recording Film 403	55 dB	23 dB	6 dB
	Recording Film 406	25 dB	53 dB	21 dB
	Recording Film 409	10 dB	23 dB	51 dB

It will be understood from the above table that
highly reliable signals were reproduced from each layer
15 with the CN ratio of not less than 50 dB and inter-layer
cross-talk from adjacent recording layers below 25 dB.

Next, another disc was produced, where thin
films composed of $\text{Ge}_{14}\text{Sb}_{29}\text{Te}_{57}$ were formed in a thickness of
2 nm as the recording films 403, 406 and 409, thin films
20 of ZnS were formed in a thickness of 50 nm as the
antireflection films 402, 405 and 408, and the rest of
the structure was completely the same as the foregoing
disc. This disc features that the transmissivity of
recorded layers decreases. For this reason, recording is
25 performed from the substrate side.

The measurement was done under the condition
that the disc structured as described above was rotated
at a linear velocity of 8 m/s (rotational speed: 1800

1 rpm, the radius: 42.5 mm), and recording was performed sequentially from the lowermost layer toward upper layers. First, the focus was placed on the recording film 409 to record thereon by irradiating a recording pulse with a recording frequency at 5.5 MHz and a duration being 90 ns. The recording power dependency of the reproduced signal intensity at that time is shown in the following table.

	Recording Power (mW)	Reproduced Signal Intensity (mV)
10	7	15
	8	85
	9	145
	10	195
	11	235
15	12	265
	13	285
	15	295

After recording on the recording film 409, the focus was placed on the recording film 406 to record thereon. The recording power dependency of the reproduced signal intensity at that time is shown in the following table.

	Recording Power (mW)	Reproduced Signal Intensity (mV)
25	7.5	20
	8.5	90
	9.5	150
	10.5	200

1	11.5	240
	12.5	270
	13.5	290
	15.5	300

5 After recording on the recording films 409 and 406, the focus was placed on the recording film 403 to record thereon. The recording power dependency of the reproduced signal intensity at that time is shown in the following table.

10	Recording Power (mW)	Reproduced Signal Intensity (mV)
	8	25
	9	95
	10	155
	11	205
15	12	245
	13	275
	14	295
	16	305

Also, the measurement results will be shown in
20 the following table as to the CN ratios at a carrier frequency of reproduced signals which were read from the recording films 403, 406 and 409 by placing the focus thereon, after signals at 3 MHz, 4 MHz and 5 MHz had been recorded on the recording films 403, 406 and 409,
25 respectively.

1		3 MHz	4 MHz	5 MHz
	Recording Film 403	54 dB	24 dB	7 dB
	Recording Film 406	26 dB	52 dB	22 dB
	Recording Film 409	11 dB	24 dB	50 dB

5 As shown in the above table, highly reliable signals were reproduced from each layer with the CN ratio of not less than 50 dB and inter-layer cross-talk from adjacent recording layers below 25 dB.

When a plastic disc of polycarbonate or acrylic resin made by injection molding was used as the substrate other than the chemical tempered glass used in the above embodiment, similar results were obtained.

Also, when Ge-Sb-Te composition, Ge-Sb-Te-M (M represents a metal element) composition, In-Sb-Te composition, In-Sb-Se composition, In-Se-M (M represents a metal element) composition, Ga-Sb composition, Sn-Sb-Se composition, Sn-Sb-Se-Te composition and so on were used as the recording film other than the foregoing In-Se-Tl composition, similar results were likewise obtained.

20 Further, other than the foregoing recording film utilizing a phase change between crystalline and non-crystalline, An In-Sb composition utilizing a crystalline-to-crystalline phase change or the like may be used as a recording film to derive similar results.

25 Particles of Bi-substituted garnet ($\text{YIG}(\text{Y}_3\text{Bi}_3\text{Fe}_{10}\text{O}_{24})$) of 20 nm in diameter were dispersed in an organic binder and spin coated to produce a recording film on a substrate similar to that shown in Fig. 11.

1 The Bi-substituted garnet of 20 nm in diameter was
produced by a coprecipitation method. The used organic
binder was that with the refractivity equal to 25. A
film thickness of the spin coated recording film was
5 about 1.5 μm , and the reflectivity (R), transmissivity
and absorptivity (k) thereof were R=8%, T=12% and K=80%,
respectively, at a wavelength of 530 nm. Since the
volume ratio of the Bi-substituted garnet in the binder
was about 60%, a rotating angle of plane of polarization
10 of a reflected light was about 0.8°. A method of
stacking a multiplicity of layers with UV cured resin
layers inserted between the layers, a method of bonding
two discs, and a recording/reproducing method were
similar to those of the foregoing embodiment. However,
15 the wavelength of a light source is selected to be $\lambda =$
530 nm.

Next, explanation will be given of an example
where an experiment was made on recording/reproduction
using the information recording medium structured as
20 shown in Fig. 12. Fig. 12A shows part of a cross-
sectional view of an information recording medium; and
Fig. 12B shows a cross-sectional view of part of a
recording layer.

A laser light guide groove with a track pitch
25 being 1.5 μm was formed in a UV cured resin layer 412 of
50 μm in thickness on a disc-shaped glass substrate 411
with a diameter of 13 cm and a thickness of 1.2 mm.
Next, a recording layer 413 was stacked by a vacuum vapor

1 deposition method. The recording layer 413 comprises two
Sb₂Se₃ layers 414 of 8 μm in thickness sandwiching a Bi
layer 415 of 3 μm in thickness, as shown in Fig. 10B.
Further, on the recording layer 413, two pairs of a UV
5 cured resin layer 412 of 30 μm in thickness formed with
laser light guide groove and the recording layer 413 were
stacked. In other words, three recording layers were
provided. On the top, a UV cured resin layer of 100 μm
in thickness was provided for the purpose of protecting
10 the recording layers. It is assumed that the recording
layers are referred to as a first recording layer, a
second recording layer and a third recording layer from
the substrate side.

A track groove was selected to be U-shaped one,
15 and the widths of a land portion and a groove portion
were both selected to be 0.75 μm. Measured reflectivities of the first, second and third recording layers
were 8.5%, 5.8% and 4.4%, respectively. Recording was
performed by irradiating each recording layer with a
20 laser light of not less than 6.0 mW. The reflectivities
of laser light irradiated portions on the first, second
and third recording layers were 18.5%, 13.0% and 9.4%,
respectively.

The change in reflectivity between the recorded
25 and unrecorded recording layers is caused by the alloying
of the recording layers. Specifically explaining, when
part of recording layer made up of two Sb₂Se₃ layers and a
Bi layer is heated by the irradiation of the recording

1 laser light, a diffusion reaction occurs between Se and
Bi, which results in alloying. Consequently, an area
with different optical constants, i.e., a recording point
is formed on the recording layer. It should be noted
5 that in the recording layer composed of Sb_2Se_3 and Bi, the
alloying causes the reflectivity and the transmissivity
to increase and the absorptivity to decrease.

Although not performed in this embodiment, if a
land portion is irradiated with a continuous laser light
10 before recording, the land portion is alloyed, with the
result that an average transmissivity per recording layer
is increased by 10%. Therefore, since the reflectivities
before and after recording are increased, this is
convenient to tracking and so on. If recording is
15 performed on both the land portion and the groove
portion, an average transmissivity per recording layer
can be likewise increased. The recording layer is not
limited to a combination of Sb_2Se_3 and Bi, but may be of
any combination as long as alloying is caused by
20 temperature rise.

Since the present invention provides light spot
focusing optical system, a disc structure, and a light
detecting optical system which enable stable recording
and reproducing in recording and reproducing processes, a
25 coding method for suppressing particularly problematic
inter-layer cross-talk, a cross-talk canceling method, a
three-dimensional data format, a disc producing method
associated with the data format, a three-dimensional

- 1 access method, highly reliable data can be recorded and reproduced by focusing a light spot on each layer of a multi-layer structured disc.